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Published in:

Proceedings of 2017 International Conference on Numerical Simulation of Optoelectronic Devices

Link to article, DOI:

[10.1109/NUSOD.2017.8010002](https://doi.org/10.1109/NUSOD.2017.8010002)

Publication date:

2017

Document Version

Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):

Rasmussen, T. S., Yu, Y., & Mørk, J. (2017). Theory and simulations of self-pulsing in photonic crystal Fano lasers. In Proceedings of 2017 International Conference on Numerical Simulation of Optoelectronic Devices (pp. 83-84). IEEE. DOI: 10.1109/NUSOD.2017.8010002

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Theory and Simulations of Self-pulsing in Photonic Crystal Fano Lasers

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Abstract—A detailed theoretical and numerical investigation of the dynamics of photonic crystal Fano lasers is presented. It is shown how the dynamical model supports self-pulsing, as was recently observed experimentally, and an in-depth analysis of the physics of the self-pulsing mechanism is given. Furthermore, it is demonstrated how different dynamical regimes exist, and these are mapped out numerically, showing how self-pulsing or continuous-wave output may be controlled through the strength of the pump and the detuning of the nanocavity. Finally, laser phase transitions through dynamical perturbations are demonstrated.

I. INTRODUCTION

Self-pulsing has in practice been an operational regime exclusive to macroscopic lasers, despite theoretical predictions [1], until recently, where experimental and theoretical demonstrations of laser self-pulsing in a microscopic photonic crystal Fano laser were published [2]. In this work, we present a detailed theoretical analysis of the physics behind the self-pulsing mechanism and laser characteristics through numerical simulations of dynamical equations describing the temporal evolution of the laser dynamics and demonstrate how the laser can undergo phase transitions from continuous wave output to self-pulsing through dynamical perturbations. The Fano laser consists of a line-defect waveguide with one end open in a 2D photonic crystal, which is coupled to a nearby point-defect nanocavity. This results in Fano interference between the discrete cavity mode and the continuum of waveguide modes, leading to a strong, narrowband transmission suppression, functioning as a Fano mirror (Fig. 1) [3]. The background dielectric contains quantum dots in both cavity and waveguide, leading to the Fano reflection coefficient depending strongly on the free carrier density in the nanocavity.

II. THEORETICAL MODEL

By setting up field equations at the mirror plane in Fig. 1, an oscillation condition is derived, which governs the threshold characteristics of the Fano laser:

$$r_L(\omega)r_2(\omega_c, \omega) = 1 \quad (1)$$

where $r_L(\omega)$ is the left reflection coefficient (including propagation phase and gain) and $r_2(\omega_c, \omega)$ is the highly-dispersive reflection coefficient of the Fano mirror, which depends explicitly on the resonance frequency of the nanocavity, derived through coupled-mode theory (CMT). Numerical solution of (1) yields the threshold gain and laser frequency as a function of laser cavity length and nanocavity resonance frequency. In

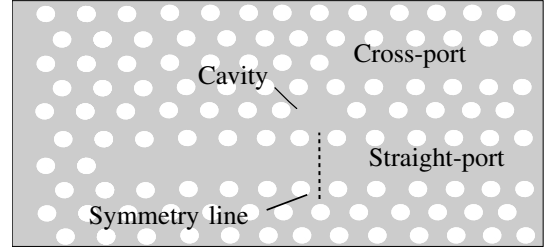


Fig. 1. Schematic diagram of the Fano laser structure, with and without annotations. The right laser mirror is realised through Fano interference between a discrete cavity mode and the continuous waveguide modes.

order to study the dynamics of the system, the field equation is expanded to first order in frequency and waveguide carrier density around a solution (ω_s, N_s) and Fourier transformed, which yields a dynamical evolution equation for the envelope of the right-propagating field in the laser cavity. This is combined with an equation for the left-propagating field envelope, derived by reformulating the CMT equation for the nanocavity field, and traditional rate equations governing the dynamics of the carrier densities in the waveguide and nanocavity respectively, yielding a system of four coupled first-order non-linear ordinary differential equations describing the dynamics of the system.

III. SELF-PULSING MECHANISM

The laser operates in states of either continuous-wave (CW) or self-pulsing output, as demonstrated in Fig. 2, which shows a phase diagram of the laser output. Here light blue represents continuous-wave output, yellow is self-pulsing and grey is below-threshold solutions. The green curve is the laser threshold current, and the dashed black line is the pulsing boundary, as calculated using a linear stability analysis, showing how the dominant mechanism of instability is relaxation oscillations becoming un-damped. Physically, the side-coupled nanocavity functions as a dispersive version of a semiconductor saturable absorber mirror (SESAM), for which Q-switched pulsing is a common phenomenon in macroscopic lasers [4]. In our microscopic system, the functionality is similar: An increase in circulating intensity leads to a saturation of the nanocavity absorption, which increases the reflectivity, in turn allowing the intensity to further increase, further saturating the cavity absorption. In this way, a positive feedback loop is established for certain parameter combinations, which allows for a sustainable dynamical equilibrium, leading to pulse trains

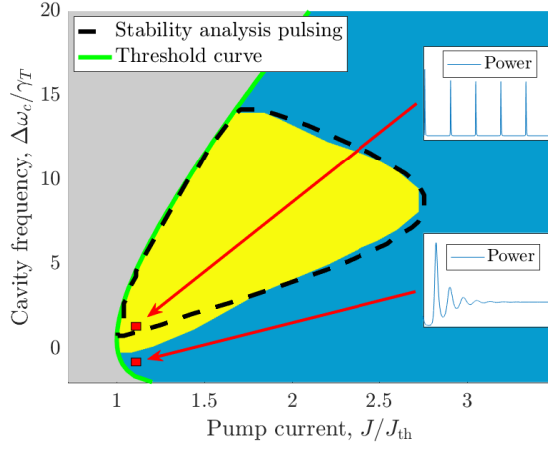


Fig. 2. Phase diagram of the laser output as a function of nanocavity resonance frequency and driving current. Light blue area represents continuous-wave lasing and yellow area represents self-pulsing. The green line is the laser threshold curve, below which the grey colour indicates absence of lasing (colour code). Insets show time evolution of straight-port output power.

with GHz repetition rate and pulsewidths on the order of 10 ps. Due to the dispersive nature of the Fano mirror, however, the amplitude-phase coupling is also highly important in establishing the dynamical equilibrium, as the laser must continually adjust its frequency to fulfil the phase condition, which in turn changes the effective reflectivity of the Fano mirror. This results in a rich physical system, for which the self-pulsing is limited primarily by two factors. First, an intensity spike must result in the reflection coefficient increasing sufficiently to power the feedback loop, i.e. the absorption cannot be saturated by the CW intensity. Second, the strong phase modulation from the amplitude changes must not detune the laser frequency so far from the reflection peak that the reflectivity variations become too weak to power the feedback loop. Figs. 3 and 4 demonstrate how a dynamical transition between the two lasing modes (insets in figure 2) takes place under dynamical detuning of the laser resonance

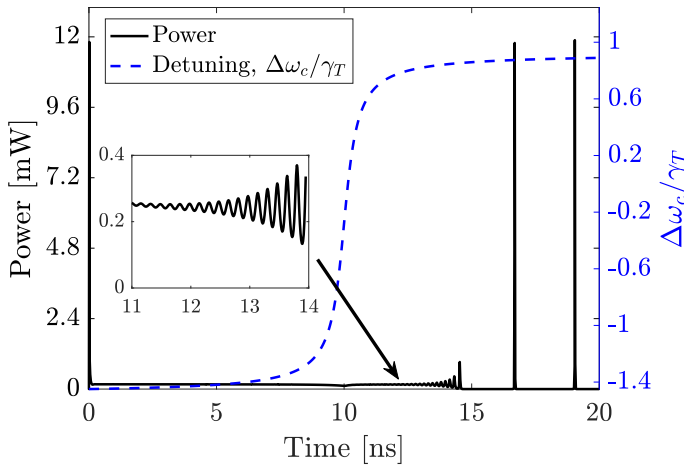


Fig. 3. Temporal evolution of laser output power as the nanocavity resonance frequency is detuned, showing how the laser transitions from CW to pulsed output by relaxation oscillations becoming un-damped. Here $J = 1.1J_{th}$ and $\Delta\omega_c$ is the difference between the cavity resonance frequency and its un-tuned value.

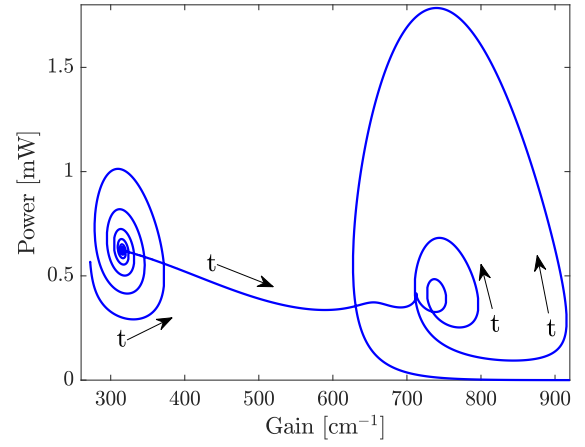


Fig. 4. Parametric plot of power as function of gain with time as the evolution parameter. This shows the evolution of a laser solution from CW into pulsed output as the cavity resonance frequency is detuned dynamically, as in Fig. 3.

frequency, with the CW solution travelling across the phase space until it reaches a point where the relaxation oscillations become un-damped, which results in a phase transition into the pulsed mode.

IV. CONCLUSION

The photonic crystal Fano laser was introduced, and a dynamical model, which supports self-pulsing, was derived. A detailed explanation of the physics behind the self-pulsing mechanism was given. The self-pulsing was shown to stem from the nanocavity functioning as a saturable absorber mirror, leading to Q-switched pulsing, but with the dispersive nature of the Fano mirror also playing an important role in establishing the dynamical equilibrium due to the strong coupling of amplitude and phase. Finally it was shown how dynamical detuning of the nanocavity resonance frequency leads to a phase transition from CW to pulsed output.

ACKNOWLEDGMENT

Financial support from Villum fonden via the center of excellence NATEC is gratefully acknowledged.

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